Synthetic Aperture Sonar Forward Modeling and Inversion

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LONG-TERM GOALS

Current and future high-resolution MCM systems such as Synthetic Aperture Sonar are actively being developed. Unfortunately, this development is proceeding in many cases without a solid understanding of how environmental effects might degrade performance or how data inversion can be used to extract information about the environment. While these systems have been largely successful in achieving their goals of producing high-resolution imagery (on the order of square centimeters), there has been little effort in linking scattering physics to both the mean levels and statistics of the resulting sonar returns seen in the images. This type of knowledge is crucial for producing both realistic forward and inverse models.

The long-term goals of the present research are to develop and validate physics-based models and inversion tools relevant to current and future synthetic aperture sonar systems. The influence of the properties of the boundaries to the scattered envelope statistics will be examined in detail as will methods to invert system data for environmental parameters. This study will yield an improved understanding of the link between environmental parameters and system factors which contribute to SAS image statistics, as well as models and methods for characterizing, predicting and mitigating environmental effects. This effort may lead to improved methods for environmental characterization (i.e., 'through-the-sensor' inversion of seafloor properties), have direct application to performance prediction, and possibly provide guidance for adaptive strategies for speckle reduction based on the operational environment.

OBJECTIVES

The importance of the present work lies in the ability to link SAS image statistics to measurable environmental properties such as seafloor roughness. In conjunction with sonar system parameters, this link will provide the foundation necessary for solving several important problems related to the detection of targets with SAS. The direct link between system and environmental parameters via scattering models to the statistical distributions will allow: performance prediction for different systems based on environmental properties, extrapolation of performance to other systems/bandwidths, and optimization of system parameters such as frequency/bandwidth to the local environment.

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Concisely the proposed objectives are:

1. Examine relationships of acoustic scattering properties (sediment interface and possibly volume for low-frequency systems) to SAS mean levels and statistics;

2. Develop predictive physics-based forward models of mean levels and statistics relevant to SAS;

3. Develop inversion tools for estimating seafloor properties based on forward models;

4. Validate forward models and inversion results against at-sea experimental data.

APPROACH

Work has been conducted recently at the Applied Research Laboratory – Penn State University (ARL-PSU) to characterize and model high-frequency scattered amplitude statistics of SAS imagery as a function of resolution, relationship to correlated seafloor structures (ripples) and propagation conditions. Work conducted with Peter Gough at the University of Canterbury in Christchurch, New Zealand, has also shown promising initial results on the possibility of inverting SAS data for large scale 2-dimensional height fields. As a follow on, the proposed research program intends to increase our understanding of how acoustic scattering processes impact SAS data in terms of both mean levels and statistics. Knowledge gained will be included in models aimed at aiding in the prediction of environmental effects on current and future MCM acoustic systems and on inversion for environmental parameters. These goals will be achieved through a close association with current PIs and projects being performed by the NSWC-Panama City. Model development will be guided by feedback from real data collected by the NSWC-Panama City.

Initial focus will be on acoustic characterization and modeling of speckle in images of ripple sandy seafloors and we will later look at more complicated scattering scenarios (e.g. seagrasses, rocky outcrops, and possibly sediment volume effects). Collaboration with the NSWC-PCD will facilitate use of their quality SAS data and results will be fed back into their program. Inversion of component forward models will also be a main priority.

WORK COMPLETED

Work was performed this year on the temporal coherence of acoustic scatter in the context of SAS coherent change detection (CCD). Acoustic data and seafloor roughness ground truth data collected during the ONR sponsored Sediment Acoustics Experiment '04 (SAX04) experiment were used to estimate the decorrelation of acoustic signals scattered from the seafloor due to changes in the shape of the seafloor interface. Acoustic data was obtaineed by a rail-mounted synthetic aperture sonar apparatus operated by the Applied Physics Laboratory –University of Washington and roughness by a digital stereo photogrammetry system. Small-roughness perturbation-theory was used to relate decorrelation of seafloor roughness spectral estimates to the decorrelation of scattered acoustic signals. The roughness ground truth-based correlation estimates ignore other probable sources of decorrelation, such as multipath, system noise, baseline decorrelation, etc., and so can be considered an upper limit to scene correlation at a given time. Results of this analysis are presented in the following section.

RESULTS

At several locations during the SAX04 experiment off the coast Florida in the northeastern Gulf of Mexico, a digital photogrammetry system supplied by the NATO Undersea Research Center was used to collect sequences of photo pairs at 10 min intervals. The system was deployed approximately 1 km off the coast of Florida, south of Fort Walton Beach, in roughly 18 m of water. For the SAX04 experiment, data sets were collected over several days at different locations. As a result of a series of tropical storms in the fall of 2004 the bottom composition at the time of the experiment for the data presented here consisted of rippled medium sand over mud patches. Via first order perturbation theory, the temporal decorrelation between signals scattered from the same patch of seafloor can be estimated using knowledge of the concurrent changes of seabed roughness. Information about the time evolution of the rough interface was obtained from the time-lapse measurements of the two-dimensional height field.

Decorrelation curves were produced for two photogrammetry sites and an example is given in Fig. 1 for site A for selected frequencies. The data have been converted to acoustic frequency using the Bragg relation for backscatter at grazing incidence. The strong frequency dependence of the temporal decorrelation is obvious from the figure. The exact dependence is specific to the mechanism responsible for changes to the seabed, in this case fish feeding. A measure of the decay rate for the decorrelation curves shown in Fig. 1 is contained in the decay constant, T, obtained by fitting exponentials of the form $Ae^{-t/T}$ to the correlation curves. Figure 2 displays the decay constant as a function of frequency for both site A and site B. The strong frequency dependence of decorrelation is obvious in this figure as is the fact that decorrelation is faster for the first site than for the second at all spatial frequencies. This result is not unexpected as the original bottom photographs as well as the DEMs showed that fish feeding at the second site appeared to have been less active than at the first site, possibly due to differences in proximity to the ship and other equipment that may have attracted fish. Figure 2 can be used to predict the repeat time for which one would expect no coherence (due to seafloor disturbance) between SAS images at a given frequency (e.g., at this site one would expect no coherence for 30-50 kHz in less than a day while for 6-10 kHz complete decorrelation would occur after several days.

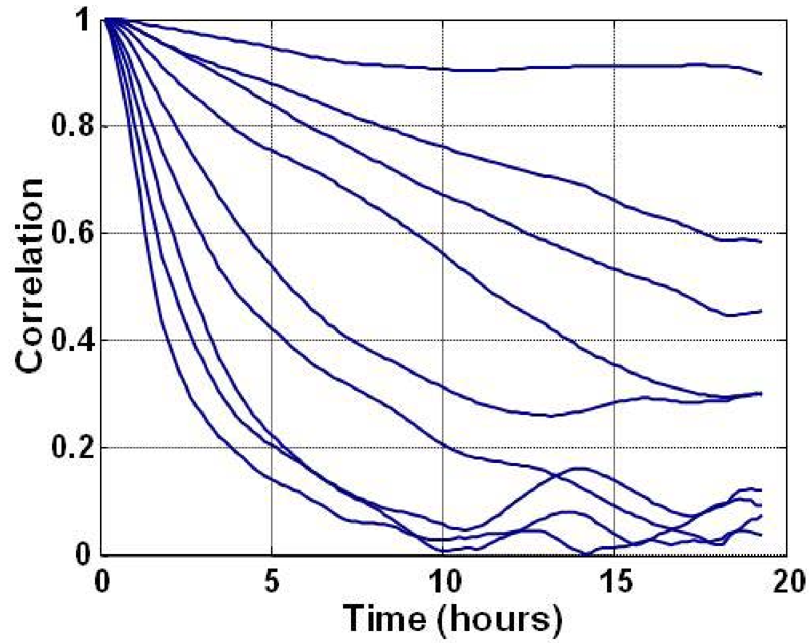

Figure 1. Site A correlation curves for (from top to bottom) 2.9, 6.6, 10.2, 13.9, 17.6, 21.2, 24.9, 28.6, and 32.2 kHz.

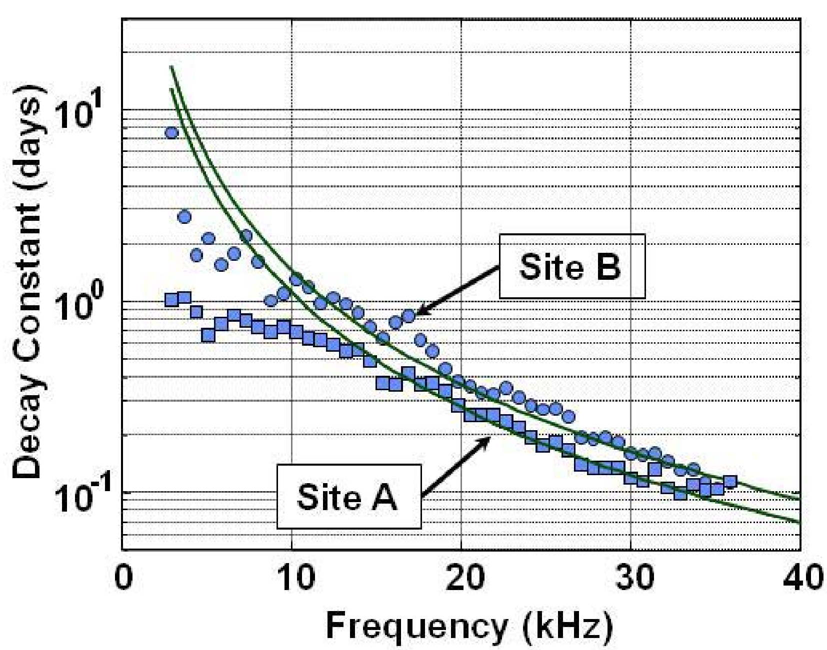

Figure 2. Decay constants as a function of frequency for sites A and B. Lines are modeled estimates of decay constant (Lyons and Brown, 2010).

Acoustic data suitable for correlation analysis were collected during SAX04 using a rail-mounted tower system operated by the Applied Physics Laboratory, University of Washington. Although data were collected over many different frequency bands with the rail-mounted system, the sample results presented here make use of only the 6–10 and 30–50 kHz bands. Transmit signals for all bandwidths consisted of 4 ms long linear frequency modulated pulses and scattered returns were collected using 10-cm vertical aperture receivers centered approximately 4.9 m above the seafloor. Each data set included waveforms recorded for 1080 transmit pulses taken in increments of 2.5 cm over a total distance of approximately 27 m. The acoustic data were unsynchronized with the photogrammetry data. Additionally, the source–receiver pair or the platform tilt angle used for a given set of transmissions was often switched from one acquisition of to the next. As a result, only a few of the data sets collected were suitable for studying SAS scene coherence for each frequency band. On these data sets we were able to examine the complex cross correlation. For the SAS data sets examined in this work, the sample coherence between two images was evaluated over a 5x5 pixel window

Figures 3 and 4 display primary SAS images used and coherence results obtained for repeat-pass SAS images taken during SAX04 for the two frequency bands. The repeat-pass times for the 6-10 kHz and 30-50 kHz sample images were 17.5 and 16 hours respectively. Magnitude images showed no visually discernable differences between the primary and secondary images with the exception of a target like feature which appeared in the 30-50 kHz band data. The low-coherence beyond approximately 20 m range seen in the results for lowest frequency band is caused by a combination of multipath and low signal-to-noise levels. For the regions where the coherence is not affected by noise, the frequency dependence of coherence for natural changes in roughness is similar to that predicted. The correlation coefficients stay above approximately 0.8 for the 6–10 kHz band and drop below approximately 0.3 for the 30–50 kHz band. Interestingly, two high-coherence areas are evident in Fig. 8. These are possibly muddy areas which may have lower bioturbation rates and hence less temporal decorrelation.

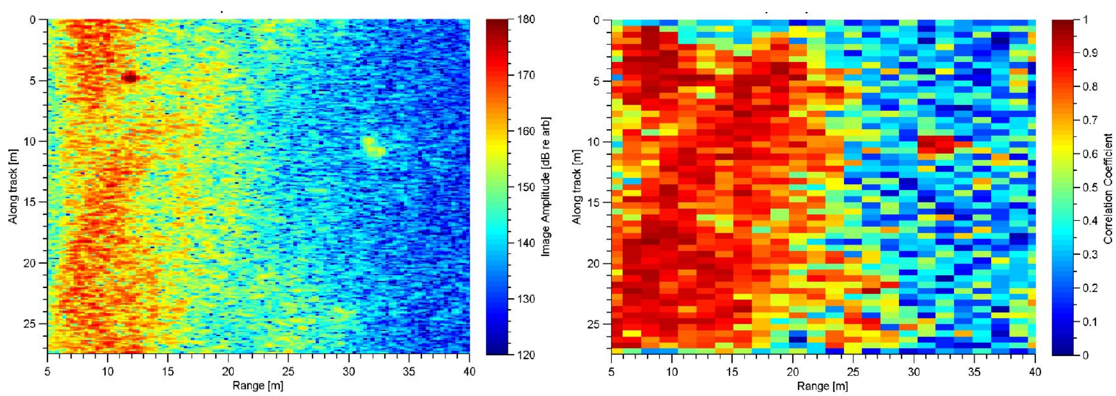

Figure 3. SAS image for 6-10 kHz band data and measured coherence for a repeat-pass time of 17.5 hours.

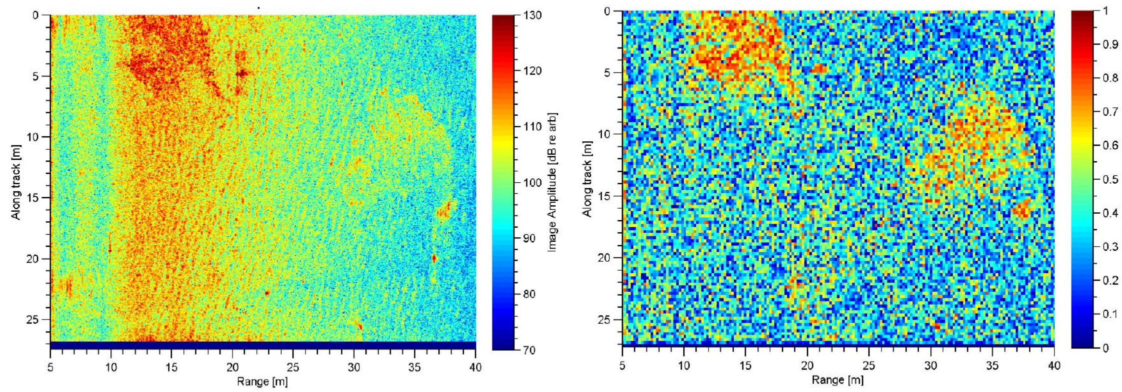

Figure 4. SAS image for 30-50 kHz band data and measured coherence for a repeat-pass time of 16 hours.

IMPACT/APPLICATIONS

SAS image statistics research is providing an improved understanding of the environmental parameters that affect high-frequency imaging systems. This study is leading to methods for modeling and predicting these environmental effects that may be used to minimize their negative impact on detection and classification of targets on or near the seafloor in shallow water. Knowledge gained will help in the development of simulation tools, adaptive systems for sonar systems and rapid environmental assessment techniques for estimating environmental parameters for a given area.

TRANSITIONS

The models of that have been explored and developed are being incorporated when possible into the ARL-PSU Technology Requirements Model (TRM), a high fidelity, physics-based digital simulator. Discussions are also under way to include models into simulations of Synthetic Aperture Sonar being developed at NSWC-Panama City.

RELATED PROJECTS

A related ONR project (Grant N00014-10-1-0051) is Statistics of High-Resolution Synthetic Aperture Sonar Imagery: Physics-Based Speckle/Texture Analysis and Simulation managed by Jason Stack, code 321OE.

PUBLICATIONS

Lyons, A.P., D.A. Abraham S.F. Johnson, 2010, Modeling the Effect of Seafloor Ripples on Synthetic Aperture Sonar Speckle Statistics, IEEE J. Ocean. Eng., 35, 242-249.

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